Effect of a Non-linear Optical Loop Mirror on the Stability of a Fibre Ring Laser Configuration

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Abstract: **Erbium doped fibre ring laser stability can be improved by an appropriate choice of laser parameters. Some of the crucial factors are explored when selecting an EDF ring laser configuration to improve the output power stability, spectral stability of the fibre laser and to increase scalability of the number of lasing wavelengths. Three ring cavity configurations have experimentally been discussed. The preferred choice of the three configurations in terms of spectral wavelength stability (within a degree of ± 0.0001), power stability of 0.4 dB and power difference of 0.4 dBm, was chosen which incorporated an external loop mirror.**

Keywords – **Dual wavelength, Erbium doped fibre, FBG, Wavelength shift, Sagnac/NOLM loop**

I. INTRODUCTION

Fibre lasers are a preferred solution for applications in new fast manufacturing processes, robot–based processing and optical communications [1] [2] [3]. The advantages of fibre lasers are that they have high power outputs, high stability, long operating lifetimes, are immune to harsh environmental changes, are compact and have lower ownership cost [1]. Fibre lasers are constructed using optical fibre with a combination of active and passive components making up the resonant cavity structure of the laser. The laser is made of three main elements as illustrated in figure 1.

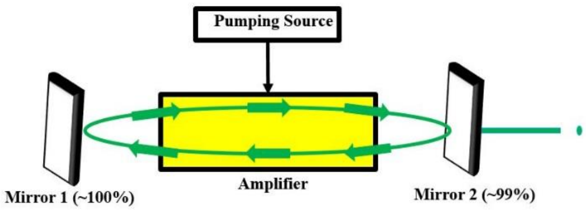

Figure 1: Resonator structure of a laser.

Figure 1 illustrates the basic component structure of a fibre laser system which consists of an amplifier, a pump source and a cavity between two mirrors.

In optical communication systems, multi-wavelength laser sources are used to produce high capacity optical networks with more bandwidth and connectivity [1] [4] [5]. Given that the operating wavelength for optical communication systems is in the 1550 nm wavelength region, erbium doped fibre (EDF) have been used as the gain medium to achieve lasing. As a gain medium, the erbium ions (Er^{3+}) are excited through pumping at a frequency of 980 nm and radiate around the 1550 nm wavelength region. The main reason wavelength division multiplex systems in communication employ the 1550 nm wavelength region is because the inherent loss in optical fibre is lowest in this region and that excellent amplifiers are available in the 1550 nm range [6] [7] [8].

In this study, the generation of dual lasing wavelengths with an erbium doped fibre ring configuration is explored which has two frequencies oscillating simultaneously. The spectral characteristics of the two wavelengths are determined by fibre Bragg gratings (FBGs) centred at 1555.12 nm and 1560.32 nm. Dual wavelength lasing (DWL) is advantageous for certain application such as sensors, communication, wavelength converters and for the generation of microwave and terahertz waves [9] [10] [11].

It has been reported that ring cavity laser configurations are susceptible to power fluctuation [10] [11] [12] [13]. These fluctuations can degrade the characteristics of sensor applications that are based on interrogation schemes as well as communication systems in which spectral and power stability is of paramount importance. The stability of the cavity configuration depends on many parameters such as the EDF length, the coupling ratio of the output coupler and the total cavity length. Some of the crucial factors to consider when selecting an EDF ring laser configuration in terms of the output power stability, spectral stability and scalability to increase the number of lasing wavelengths, are:

- The homogeneous spectrum broadening of EDF at room temperature leads to strong mode competition, resulting in unstable lasing [10] [11] [12] [13] [14].

- For a long cavity length, there is a large number of densely spaced longitudinal modes that are generated and an ultranarrow bandwidth mode selection mechanism must be incorporated to ensure single longitudinal mode (SLM) operation [10] [11] [12] [13] [14].

II. Experimental Design

In this section, the experimental design of the erbium doped fibre ring laser configuration to achieve dual wavelength lasing, is discussed. Simultaneous output power increase with pump power, and the power stability of the two wavelengths is of paramount importance. As such, the objective of performing experiments was not only to achieve dual wavelength lasing but also to have comparative power stability and wavelength spectral stability between the wavelengths. The experimental approach was divided into three main sections and each experimental objective is summarised below.

Experiment 1: To achieve dual wavelength lasing.

Experiment 2: To improve the power difference between the wavelength output power and improve the output power stability.

Experiment 3: To simplify the erbium doped fibre ring laser configuration.

Lastly, the three configurations from each experiment were analysed to choose the most appropriate configuration in terms of spectral characteristic stability and power stability.

A. EXPERIMENT 1: DESIGN (METHOD AND APPARATUS)

The experimental EDF laser configuration is shown in figure 2. The configuration is made up of a ring cavity with two FBGs (Bragg wavelengths centred at 1555.12 nm and 1560.32 nm, each grating has a bandwidth and reflectivity of 0.183 nm, 0.195 nm and 96.01 %, 96.35 %, respectively). The ring cavity is completed by the series connection of a WDM coupler, an EDF of length 3,2 m with an absorption of 11.38 dB/m at 980 nm, an optical isolator and three optical couplers. The EDF pump source is a laser diode (LD, FOL0907 series with a LM14S2 LD mount) centred at 967 nm.

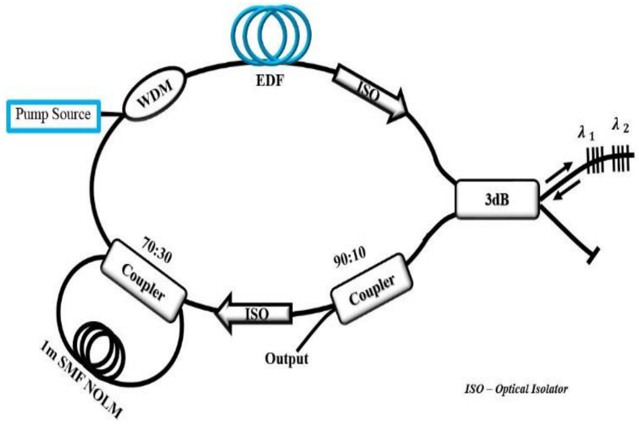

Figure 2: Dual fibre ring laser schematic with two gratings at 1555.12 nm and 1560.32 nm (experiment 1) [15].

The use of the three optical couplers in the configuration shown in figure 2 may be summarised as follows, the 3 dB coupler is used to attach the FBGs to the cavity for wavelength selection; while a coupler with a 90:10 coupling ratio is used to couple 10 % of the light out of the cavity and 90 % fed back into the cavity. The 70:30 coupler, was used to form a nonlinear optical loop mirror (NOLM) to introduce wavelength dependent loss and intensity dependent loss within the cavity. This was done to balance the loss and gain between the two wavelengths to achieve dual wavelength lasing. [10] [14] [16]. Simultaneous wavelength lasing depends on the internal cavity loss across each wavelength. To suppress the gain competition and mode competition in the cavity, an external loop was connected to the ring cavity. The loop would act as a saturable absorber, which is a mechanism that operates as an auto tracking band filter that selects the dominant mode [19]. It has been reported in [8] and [17] that, in conventional EDF lasers, the dominant mode may change because of mode competition, thus, affecting stability. However, with proper gain mode competition suppression, packaging and temperature compensation, a stable single longitudinal mode ring laser can be achieved [8] [18] [19].

1) Spectral Characteristics

The 3 dB coupler and a 70:30 coupler with a 30 % looping over a 1 m single mode fibre in the laser configuration shown in figure 3, were used to introduced intensity and wavelength dependent loss to ensure that dual lasing at the 1555.12 nm and 1560.32 nm wavelengths were produced. The combination act as cavity loss controllers to eliminate the difference in spectral gain to achieve equal power. These wavelengths were the ones at which the loss is low enough to match the available gain. The laser output spectrum of the ring cavity configuration of figure 2 is shown in figure 3. It illustrates the full-width at half maximum (FWHM) spectrum of the dual wavelength laser 0.19 nm and 0.2 nm and single longitudinal mode (SLM) wavelengths lasing at 1555.12 nm and 1560.32 nm [10] [11] [12], showing similar spectral power and spectral widths (within 2 nm). Figure 3 also shows that dual lasing was achieved with an optical signal to noise ratio (OSNR) of more than 70 dB and the spectral effect that an increase in pump power has on the two generated wavelengths. It is shown that as the pump power increases, the output lasing spectra increases simultaneously, meaning that there is a balance between the two-wavelength's power increases relative to the pump power. The figure also shows that as the pump power is increased, SLM wavelength lasing is not lost as the output power increases. In addition, figure 3 shows there is no visible wavelength spectral shift above the ± 0.0001 degree for the two individual lasing wavelengths.

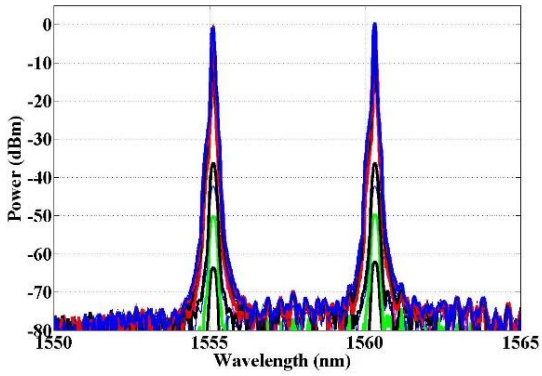

Figure 3: Laser spectrum at 1555.12 nm and 1560.32 nm for different pump power (experiment 1).

The experiments for the output power stability and spectral wavelength stability were performed under constant temperature conditions.

B. EXPERIMENT 2: DESIGN (METHOD AND APPARATUS)

The previous section showed that a dual wavelength erbium doped fibre ring laser can be achieved with the configuration shown in figure 2**.** The experimental setup of the new configuration is shown in the schematic of figure 4. Some of the possible improvements that were considered were changing the position of the isolator placed between the 90:10 optical coupler and 70:30 optical coupler with the NOLM. Initially, the isolator was used to isolate the output coupler from the reflections from the NOLM, however, the reflections from the output coupler to the 3 dB coupler may have a more direct influence on the lasing wavelengths selected by the FBGs. Reflections from the 90:10 coupler that interfere with any of the two-wavelength selected by the FBGs have a direct impact on the stable lasing wavelengths because of the position of the output coupler. As such, repositioning the isolator may result in a reduction of the reflections to the FBGs thereby increasing the stability of dual lasing. The reflections from the NOLM may contribute to the wavelength and intensity dependent loss in the cavity required to sustain dual wavelength lasing.

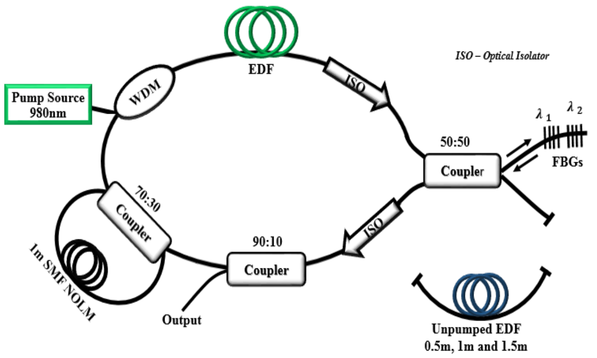

Figure 4: Proposed schematic of the dual wavelength erbium doped fibre ring laser (experiment 2) [20].

As in figure 2 the same component specification described was used in this setup. The ring cavity unidirectional flow of light was guaranteed by the two polarization independent isolators connected to a 3 dB (50:50) coupler to which the two FBGs were attached. The NOLM has been connected to the 30 % output coupling of the 70:30 optical coupler to introduce cavity loss for dual lasing.

For this configuration, the threshold power for the two wavelengths was not the same. The 1555.12 nm wavelength threshold was lower than that of the 1560.32 nm wavelength, because of the unevenness of the gain medium distribution of the EDF [19] [21] [22]. The gain required at the 1560.32 nm wavelength was required to be equal to that of the 1555.12 nm wavelength however, it was lower.

It is discussed in [21] [23] [18] [24] and [25] that introducing intensity or wavelength dependent loss in the cavity may flatten the gain profile. If the loss introduced is across the 1560.32 nm wavelength, this will allow the adjustment of the gain across the 1560.32 nm wavelength to be greater than the loss, resulting in lower pump power needed to start lasing. The aim was to obtain a stable dual wavelength laser with simultaneous output power increase characteristic relative to an increase in the pump power. The looping mechanism and change in cavity length was used to investigate the prospect of attaining a uniform output power increase relative to increase in pump power and to improve the power stability between the dual wavelengths of the EDF ring laser shown in figure 4.

Figure 5 illustrates the effect of the interference caused by the bidirectional flow of light in the NOLM loop on the laser wavelength characteristics as the laser output increases with an increase in the pump power. Figure 5.(a) shows the laser output when there is no loop and figure 5.(b) shows the laser output with the 1m SMF loop as indicated by the schematic in figure 4.

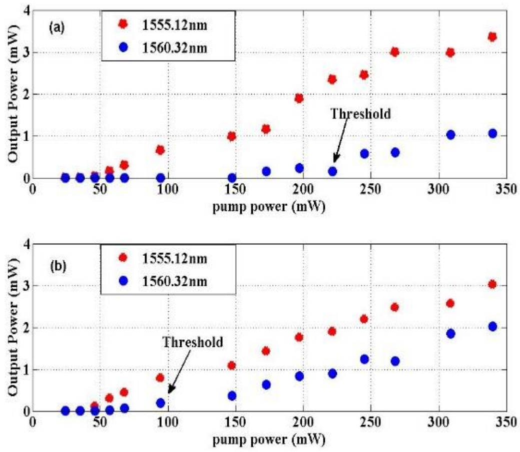

Figure 5: Illustration of the effect of the NOLM on the threshold of the lasing wavelengths, (a) no loop and (b) 1m SMF loop (experiment 2).

The loop results in a lower threshold power for the 1560.32 nm (blue) wavelength than when there was no optical loop and indicated that by changing the parameters of the looping, the threshold of the two-lasing wavelength is equal.

It is reported in [10] that to ensure stable operation of the dual wavelengths of an EDF ring laser, two issues must be considered. One of these is, because of the long cavity length (typically above 10m) of the fibre laser, the longitudinal modes are closely spaced resulting in multi-longitudinal mode oscillation and mode hoping [9] [10]. This second issue includes the homogeneous broadening of EDF at room temperature which leads to mode competition and unstable lasing [9] [10]. This may be solved by introducing an ultra-narrow bandpass filter (BPF) with two transmission peaks to eliminate multi-longitudinal mode oscillation and mode hopping. The ultra-narrow BPF can be realised by using a saturable absorber based on an optical loop mirror (Sagnac loop) [26] [27] [19], a multi–ring loop with a BPF [12] [28], phase–shifted FBG or a Fabry perot filter [9] [10].

2) Results: Spectral Characteristics

The spectrum of the dual wavelength EDF fibre ring cavity laser of figure 4 is shown in figure 6. It demonstrates SLM wavelength lasing at both the 1555.12 nm and 1560.32 nm wavelength [5] [7] [8]. The dual wavelengths have a FWHM of 0.19 nm and 0.20 nm respectively. Their power levels are 2.3 mW and 2,5 mW with a power difference of 0.4 dBm. An OSNR of more than 70 dB (a measurement of the ratio of signal power to noise power ratio) was achieved with the ring cavity.

Figure 6 shows that as the pump power increases, the output lasing spectra increases equally. The respective full width half maximum (FWHM) peak power of the two wavelengths were measured to be 3.5 dBm (2.3 mW) at 1555.12 nm and 3.9 dBm 2.5 mW at 1560.32 nm (pump power of 23.334 dBm) with an optical spectrum analyser (AQ-6315B).

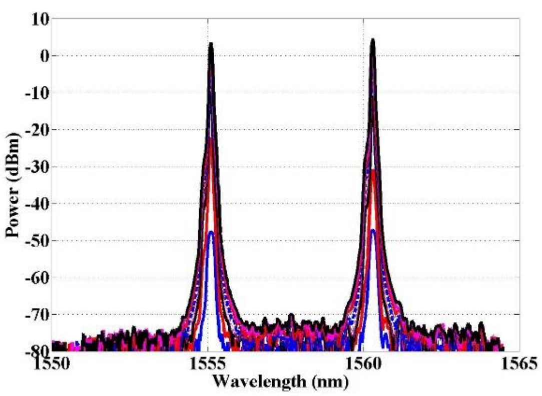

Figure 6: Laser spectrum at 1555.12 nm and 1560.32 nm for different pump power (experiment 2).

As in figure 3, figure 6 shows there is no visible wavelength spectral shift above the ± 0.0001 degree for the two individual lasing wavelengths as the pump power was increased. The experiments for output stability and spectral wavelength stability were performed under constant temperature conditions so that the result for each experiment may be assumed to be independent of the temperature influence to isolate the effect of mode competition in the laser cavity on the spectral drift of the individual wavelengths.

C. EXPERIMENT 3: DESIGN (METHOD AND APPARATUS, NO EXTERNAL LOOP)

The looping mechanism and change in cavity length was used to investigate the prospect of attaining a uniform output power increase relative to an increase in pump power and to improve the power stability between the dual wavelengths of the EDF ring laser shown in figure 4.

The experimental setup of the new ring cavity configuration is shown in figure 7. The aim was to test whether comparable results will be attained when removing the external loop attached to the ring cavity configuration.

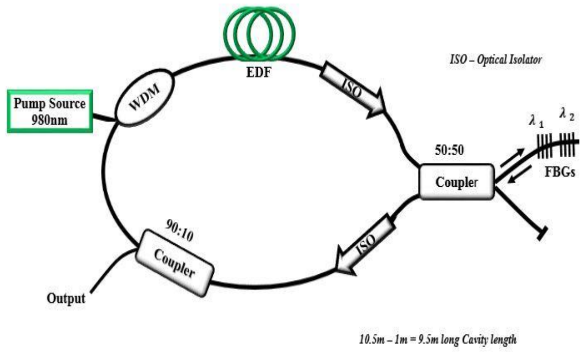

Figure 7: Schematic of the dual wavelength erbium doped fibre ring laser (experiment 3).

As in figure 4, two FBGs, centred at 1555.12 nm and 1560.32 nm were externally connected in series to the cavity and were used to select the operating wavelengths of the resonator. The ring cavity unidirectional flow of light was guaranteed by the two polarization independent isolators connected to the 3 dB coupler to which the two FBGs were attached. The results are shown and discussed in the next section.

3) Results: Spectral Characteristics

The spectrum of the dual wavelength EDF fibre ring cavity laser configuration in figure 7 is shown in figure 8. The figure demonstrates single longitudinal mode wavelength lasing at both the 1555.12 nm and 1560.32 nm wavelength [10] [11] [12]. The dual wavelengths have a FWHM of 0.19 nm and 0.2 nm respectively. Their power levels were 2.5 mW and 2.6 mW respectively. An OSNR of more than 70 dB was achieved with the ring cavity.

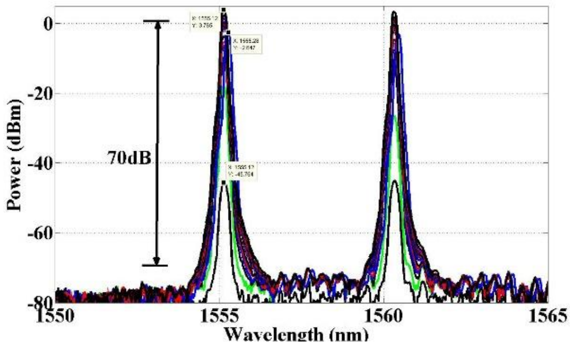

Figure 8: Laser spectrum at 1555.12 nm and 1560.32 nm for different pump powers (experiment 3).

Figure 8 also illustrates the spectral effect that an increase in pump power has on the two generated wavelengths. It is shown that as the pump power increases, the output lasing spectra increases equally. However, there is a visible wavelength spectral shift in the two individual lasing wavelengths at an output power of -2.647 dBm (spectrum indicated by blue colour in figure 8). The shift deviated 0.16 nm from the central wavelengths of 1555.12 nm and 1560.32 nm. It is discussed in [10] and [11] that a saturable absorber operates as an auto-tracking narrow band filter, which selects the dominant mode. This motivates the use of the externally connected loop in maintaining spectral stability of the dual lasing wavelengths. A filter-less cavity may stimulate wavelength emission at a random wavelength based on the cavity loss of the configuration [11] [29] [30] and demonstrated the mode competition that occurred within the cavity. Thus, it is concluded that the loop plays a key role in maintaining spectral stability within the cavity

III. DISCUSSION AND CONCLUSION

Three ring cavity configurations have experimentally been discussed. Dual wavelength lasing was achieved with the configuration shown in figure 2. The lasing wavelengths were defined by the fibre Bragg gratings with reflectivity's at 1555.12 nm and 1560.32 nm. A 1.5 dB power stability of both wavelength was achieved with this configuration. The configuration used could maintain the spectral widths at 0.19 nm and 0.20 nm specified by the FBGs with no spectral shift. A noise suppression of 70 dB was obtained.

The 1.5 dB stability obtained with the configuration in figure 2 is considerably better than the 2.4 dB stability obtained in [19]. The configurations in [19] and figure 2 both use a 3 dB optical coupler in a WSC arrangement, however the two FBGs in [19] are connected in parallel with a VA connected to each FBG while the FBGs in figure 2 are in series. This showed that the EDF ring cavity configuration shown in figure 2 can be improved. Further attempts were made to improve the configuration power stability and power difference [15].

The configuration shown in figure 2 was then changed to the configuration of figure 4. An improved stable dual wavelength laser was realized with a NOLM and cavity length change on the oscillating wavelength characteristics of the fibre laser. The stability of the dual lasing wavelengths was investigated using an optical loop mirror with a 1m length of single-mode fibre and changing the cavity length on the uniformity of the wavelength power increase relative to an increase in pump power [20].

A good prospect of a stable dual wavelength erbium doped fibre ring laser is achieved with the configuration shown figure 4. The power stability is comparable with the results that were obtained in [10] and in [18] and is better than the power stability of 2.4 dB and 1.5 dB from the configuration in [19] and figure 2, respectively. The change in the component arrangement of the ring cavity configuration of figure 2 to figure 4 has made a valuable contribution to the power stability across the two wavelengths (1555.12 nm and 1560.32 nm). A power stability of 0.35 dB and 0.2 dB at 1550.9 nm and 1562.8 nm respectively, was obtained with laser configuration in [10]. Considering the ring cavity configuration [10] employs a dual WSC arrangement based on circulators, the 0.4 dB stability of figure 4, which used a combination of isolator and coupler as the WSC arrangement is a good result considering WSC arrangement with circulators achieve better stability.

However, upon realising that it was possible to achieve stable dual wavelength lasing without the use of the NOLM, the loop was removed. To summarise the results of changing the configuration from figure 4 to figure 7 (from experiment 3), good output power linearity relative to pump power and power stability 0.3 dB was achieved. However, there was a spectral shift of the two lasing wavelengths at an output power of -2.647 dBm. The shift was 0.16 nm from (to the right) the central wavelengths of 1555.12 nm and 1560.32 nm. The spectral characteristics that were produced by the configuration shown figure 2 and figure 4 indicated no measurable spectral shift when compared to that of figure 7. As such figure 4 represent the preferred choice of the three configurations in terms of spectral wavelength stability (to the degree of ± 0.0001), power stability (0.4 dB) and power difference which is 0.4 dBm. The ring cavity configuration with both power and wavelength stability consist of an external NOLM with a 1m long sing-mode fibre contrary to the schematic of figure 7 which has no external loop attached.

The results represent a good prospect for achieving better stability with a cheaper configuration without the use of circulators and variable attenuators. The uniqueness of the ring cavity configuration is that it employed a 3.2 m long EDF to obtain dual wavelength laser. The combination of the components gave an OSNR of more than 70 dB. Some of the ring cavity configurations in literature use EDF lengths that are greater than 5m and achieve OSNR's of less than 70dB [5] [18] [31] [10] [18] [19].

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